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Mathematical Modeling of a Photovoltaic-Laser Energy Converter For Iodine Laser Radiation

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Space-based laser power systems will require converters on power receiving spacecraft to convert laser radiation to electricity. Candidate converters are: magnetohydrodynamic (MHD) generators; heat engines; optical rectifiers; reverse free electron lasers; and photovoltaic converters (refs. 1 and 2). This report will emphasize the calculated characteristics of one type of photovoltaic converter.

Properly designed silicon laser-photovoltaic converters have calculated conversion efficiencies greater than 50 percent (ref. 3) for 1.06 μm, high intensity laser radiation. Vertical junctions were used for these laser-photovoltaic converters (ref. 3).

A candidate laser for power system applications is the iodide t-C₄F₉I laser (ref. 4). This laser emits radiation at a wavelength of 1.315 μm or 0.943 eV. The semiconductor for a photovoltaic converter used at this wavelength should, for efficient conversion, have a bandgap energy slightly
less than the laser photon energy (ref. 5). None of the commonly used elemental and binary semiconductors have bandgap energies near 0.943 eV (ref. 6). By adjusting the amount of GaAs and InAs in the ternary semiconductor Ga_{1-x} In_{x} As, bandgap energies from 0.36 eV to 1.42 eV can be realized. A bandgap energy of 0.94 eV has been reported for the semiconductor Ga_{.53}In_{.47}As (ref. 7). This bandgap energy was near the laser photon energy. Absorption coefficients and material parameters for Ga_{.53}In_{.47}As are not available in the literature. However, since Ga_{.53} In_{.47} As is a III-V, direct bandgap semiconductor containing GaAs, the absorption coefficients and material parameters were approximated by shifting GaAs parameters to correspond to the 0.94 eV bandgap energy of Ga_{.53}In_{.47}As (ref. 8 and a private communication with M.F. Lamorte). Figure 1 shows the absorption coefficients used in this study (ref. 9).

The model described in reference 5 was used along with the material parameters for Ga_{.53}In_{.47}As to define optimum converter design parameters. A set of baseline converter parameters shown in Table I was assigned. Each of these parameters was then optimized individually. Figure 2 shows the configuration of a single vertical junction converter mounted on a heat pipe. For the bandgap energy of 0.94 eV, the baseline efficiency was 40.3 percent.

### Converter Width

Figure 3 shows the effect of increasing the converter width with the p-n junction located 2.5 x 10^{-4} cm (2.5 μm) from one edge. The efficiency increases from 21.9 percent at a width of 1 x 10^{-3} cm (10 μm) to 50.0 percent at a width of 3.0 x 10^{-4} cm (3.0 μm). Although narrower converters have a slightly higher efficiency, from a fabrication viewpoint, 3.0 x 10^{-4} cm (3.0 μm) is taken as the optimum converter width.
Junction Position

The junction position must be optimized for each converter width. Figure 4 shows the effect of changing the junction position for our optimum width of 3.0 x 10^{-4} cm (3.0 μm). The efficiency increases from 33.7 percent at a junction position of 5.0 x 10^{-5} cm (0.5 μm) to a peak of 50.5 percent at a junction position of 2.5 x 10^{-4} cm (2.5 μm). The efficiency increases because of an increase in the width of the higher diffusion length p material. The efficiency is optimum for a junction position of 2.5 x 10^{-4} cm (2.5 μm). We choose this value for our optimum converter.

Converter Thickness

Figure 5 shows the effect of converter thickness on converter efficiency. The efficiency increases from 9.8 percent at a thickness of 1 x 10^{-4} cm (1.0 μm) to 40.3 percent at a thickness of 3 x 10^{-3} cm (30.0 μm). For our optimized converter, we choose a thickness of 3 x 10^{-3} cm (30.0 μm).

Series Resistance

Figure 6 shows the effect of varying the series resistance for our baseline converter. The efficiency varies from 40.3 percent for a series resistance of 1 x 10^{-3} ohms to 20.7 percent for a series resistance of 1.0 ohms. The Ga_{0.53}In_{0.47}As material in our optimized converter has a calculated resistance of 1.14 x 10^{-4} ohms. To allow for some contact resistance, we have chosen 2.0 x 10^{-4} ohms as the series resistance of our single element, optimized converter.
Converter Temperature

The converter for this study is assumed to be mounted on a heat pipe for temperature control under conditions of high incident power density. The temperature of the converter is controlled by the temperature of the heat pipe and by the heat transfer coefficient for the converter-heat pipe interface. Figure 7 shows the converter efficiency as a function of temperature. The efficiency at 250 K is 41.4 percent while the efficiency at 480 K is 18.2 percent. We specify that our optimum converter operate at a heat pipe temperature of 20°C.

Carrier Concentration

Figure 8 shows the effect of acceptor concentration on converter efficiency. The peak efficiency of 41.2 percent occurs for an acceptor concentration of $1 \times 10^{18}$ carriers/cm$^3$. Figure 9 shows that the peak efficiency of 48.7 percent occurs for a donor concentration of $1 \times 10^{17}$ carriers/cm$^3$. For our optimum converter, we choose an acceptor concentration of $1 \times 10^{18}$ carriers/cm$^3$ and a donor concentration of $1 \times 10^{17}$ carriers/cm$^3$ corresponding to the peak efficiencies.

Surface Recombination Velocity

Figures 10 and 11 show the effect of surface recombination velocity on the converter efficiency. For the n-contact surface, the efficiency decreases from 40.4 percent at a surface recombination velocity of 1 cm/sec to 26.4 percent at a surface recombination velocity of $1 \times 10^7$ cm/sec. For the p-contact surface, the efficiency decreases from 40.7 percent at a surface
recombination velocity of 1 cm/sec to 36.4 percent at a surface recombination velocity of $1 \times 10^7$ cm/sec. According to reference 10, GaAs interfaces have surface recombination velocities of $1 \times 10^4$ cm/sec; therefore, we have chosen $1 \times 10^4$ cm/sec as a realistic value of the surface recombination velocity for our optimum converter.

### Optimized Converter

Table II shows the parameters of our optimized converter. Figure 12 shows the efficiency of this optimized converter as a function of input power density. The efficiency increases from 33.4 percent at 1 w/cm$^2$ to an efficiency of 48.6 percent at $1 \times 10^3$ w/cm$^2$.

### Multijunction Converter

The above calculations are for a single element, vertical junction converter, whereas in reality, a practical device would consist of many of these optimized vertical junctions connected in series as is shown in figure 13. Applying the parameters for our optimized, single element converter to a 1000 junction converter gives the efficiency as a function of power density shown in figure 14. The efficiency varies from 27.4 percent at 1 w/cm$^2$ to 42.5 percent at $1 \times 10^3$ w/cm$^2$. 
Conclusions

Our mathematical model has been applied to a 0.94 eV photovoltaic converter designed for the 1.315 \( \mu m \) line of an iodine laser. The semiconductor that has a bandgap suitable for use with this laser was Ga\(_{53}\)In\(_{47}\)As. By assuming that this III-V direct bandgap semiconductor has absorption coefficients similar to that of GaAs, an optimized converter has been designed. The efficiency of our optimized 1000 junction converter was 42.5 percent at a power density of 1.0 \( \times 10^3 \) w/cm\(^2\). This converter was conceived for use with a solar-pumped iodine laser as part of a space-based laser power system.
Table I

Baseline Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Series Resistance</td>
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<tr>
<td>Heat Pipe Temperature</td>
<td>20°C</td>
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<tr>
<td>Heat Transfer Coefficient</td>
<td>100</td>
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<tr>
<td>Recombination Velocity on n-surface</td>
<td>1000 cm/sec</td>
</tr>
<tr>
<td>Recombination Velocity on p-surface</td>
<td>1000 cm/sec</td>
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<tr>
<td>Input Power Density</td>
<td>1 kw/cm²</td>
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<tr>
<td>Laser Wavelength</td>
<td>1.315 μm</td>
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<tr>
<td>Converter Thickness</td>
<td>3.0 x 10⁻³ cm</td>
</tr>
<tr>
<td>Converter Width</td>
<td>5.0 x 10⁻⁴ cm</td>
</tr>
<tr>
<td>Converter Length</td>
<td>1 cm</td>
</tr>
<tr>
<td>Junction Position</td>
<td>2.5 x 10⁻⁴ cm</td>
</tr>
<tr>
<td>Acceptor Carrier Concentration</td>
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</tr>
<tr>
<td>Donor Carrier Concentration</td>
<td>6.0 x 10¹⁷ carriers/cm³</td>
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<tr>
<td>Reflection Coefficient</td>
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<tr>
<td>Shunt Resistance</td>
<td>1 x 10⁶ ohms</td>
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</tbody>
</table>
## Table II

**Optimized Parameters**

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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series Resistance</td>
<td>$2 \times 10^{-4}$ ohms</td>
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<tr>
<td>Heat Pipe Temperature</td>
<td>20°C</td>
</tr>
<tr>
<td>Recombination Velocity on n-surface</td>
<td>$1 \times 10^4$ cm/sec</td>
</tr>
<tr>
<td>Recombination Velocity on p-surface</td>
<td>$1 \times 10^4$ cm/sec</td>
</tr>
<tr>
<td>Laser Wavelength</td>
<td>1.315 $\mu$m</td>
</tr>
<tr>
<td>Converter Thickness</td>
<td>$3 \times 10^{-3}$ cm</td>
</tr>
<tr>
<td>Converter Width</td>
<td>$3.0 \times 10^{-4}$ cm</td>
</tr>
<tr>
<td>Converter Length</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>Junction Position</td>
<td>$2.5 \times 10^{-4}$ cm</td>
</tr>
<tr>
<td>Acceptor Carrier Concentration</td>
<td>$1 \times 10^{18}$ carriers/cm$^3$</td>
</tr>
<tr>
<td>Donor Carrier Concentration</td>
<td>$1 \times 10^{17}$ carriers/cm$^3$</td>
</tr>
<tr>
<td>Reflection Coefficient</td>
<td>0.05</td>
</tr>
<tr>
<td>Shunt Resistance</td>
<td>$1 \times 10^6$ ohms</td>
</tr>
</tbody>
</table>
References


Figure 1 - Absorption coefficients for Ga$_{53}$In$_{47}$As

Figure 2 - Single vertical junction converter mounted on a heat pipe

Figure 3 - Efficiency vs. converter width

Figure 4 - Efficiency vs. junction position
Figure 5 - Efficiency vs. converter thickness

Figure 6 - Efficiency vs. series resistance

Figure 7 - Efficiency vs. converter temperature

Figure 8 - Efficiency vs. acceptor concentration
Figure 9 - Efficiency vs. donor concentration

Figure 10 - Efficiency vs. recombination velocity on n-surface

Figure 11 - Efficiency vs. recombination velocity on p-surface

Figure 12 - Efficiency of optimized single junction converter as a function of incident power density
Figure 13 - Schematic diagram of series-connected, multiple junction converter

Figure 14 - Efficiency vs. input power density for an optimized, 1000 junction, series-connected converter
### Mathematical Modeling of a Photovoltaic-Laser Energy Converter for Iodine Laser Radiation

**Title and Subtitle**

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**Abstract**
Space-based laser power systems will require converters to convert laser radiation to electricity. Vertical junction photovoltaic converters are promising devices for this use. A promising laser for the laser power station is the t-C₄F₇I laser which emits radiation at a wavelength of 1.315 μm. This paper describes the results of mathematical modeling of a photovoltaic-laser energy converter for use with this laser. The material for this photovoltaic converter is Ga₅₃In₄₇ which has a bandgap energy of 0.94 eV, slightly below the energy of the laser photons (0.943 eV). Results of a study optimizing the converter parameters are presented. Calculated efficiency for a 1000 vertical junction converter is 42.5 percent at a power density of 1 x 10³ w/cm².

**Key Words**
- Energy conversion
- Photovoltaic converters
- Solid-State devices
- Laser-Energy conversion

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